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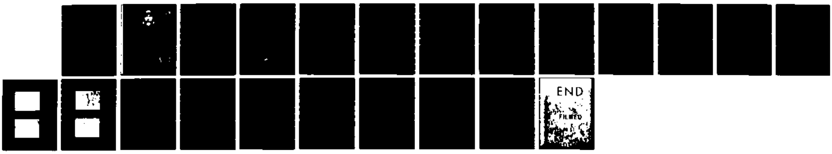

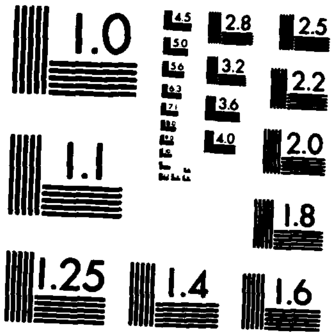

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Materials Report 82-M

CRACK INITIATION AND PROPAGATION PROPERTIES OF HY 130 STEEL WELDMENTS FOLLOWING TEMPER EMBRITTLEMENT

K.I. McRae

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CRACK INITIATION AND PROPAGATION PROPERTIES OF HY 130 STEEL WELDMENTS FOLLOWING TEMPER EMBRITTLEMENT

K. McRae

September 1982

Approved by:

Section Head

C/DREP

Research and Development Branch
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Abstract

Elastic-plastic fracture mechanics (EPFM) may be applied to engineering problems to determine material properties related to crack initiation and propagation. Specifically, these concepts have been applied to a study of the "as welded" and temper embrittled weldments of HY 130 steel. The property relating the energy requirement for ductile crack initiation, J_{IC} or K_{IC}, is seen to be similar in both instances, although previous Charpy V-notch testing results have indicated large differences in toughness. The sensitivity to embrittlement is reflected, however, by a large difference in the crack propagation property, the tearing modulus, T. The data are also compared to crack initiation and crack propagation energies measured during instrumented impact tests.

Introduction

The application of linear elastic fracture mechanics (LEFM) to engineering fracture analyses has become increasingly widespread and the use of the critical stress intensity parameter, K_{Ic}, has proven valid and useful if plane strain conditions are maintained in the specimen or structure. However, many modern engineering materials possess high fracture toughness and, therefore, require very large specimen sizes to maintain valid plane strain conditions required for (LEFM) fracture toughness testing[1]. Also, in many instances, an engineering structure, such as an aircraft wing, will contain thin section components that fracture under totally plane stress conditions. There was clearly a requirement for parameters which reflect real fracture conditions and which were measurable utilizing the smaller specimen dimensions which more accurately represent the engineering structures to which the particular material was to be applied. The advent of elastic-plastic fracture mechanics (EPFM) has proven valuable because a critical fracture initiation parameter, J_{Ic}, may be determined to provide a measure of the strain energy released at fracture initiation and may also be measured by the use of relatively small specimens. A second parameter, which provides a measure of the resistance to crack propagation, the tearing modulus, T, may also be calculated by elastic-plastic fracture analysis. In addition, estimates of the plane strain stress intensity, K_{Ic}, may be made via a simple relation to the critical elastic-plastic parameter, J_{Ic}.

In recent years, DREP[2,3,4] and the University of British Columbia[5,6] have completed several investigations regarding the marine applications of HY 130 steel and its weldments. These investigations have included Charpy V-notch and LEFM fracture analyses of both parent and stick welded air-melted, vacuum-degassed (AMVD) HY 130 steel. This previous work has demonstrated that weld stress relief heat treating procedures may result in significant temper embrittlement of the weld[3,6]. This present investigation compares the appropriate elastic-plastic parameters in the normal and temper embrittled HY 130 weldments. These data will also be correlated to a fractographic comparison of the two material conditions.

Method for J_{Ic} and Tearing Modulus Determination

Several possible methods exist for the measurement of J_{Ic} in small three-point bend or modified compact tension specimens. These include an accurate multiple specimen technique and a variety of single specimen techniques utilizing methods such as specimen unloading compliance, AC and DC potential drop, ultrasonics and acoustic emission as a means of determining the point of crack initiation. In every instance, the primary concern is the determination of the precise point at which ductile crack growth commences, with a minimum of ductile crack propagation. Recently, the ASTM Committee E24 has produced a document[7] which is intended to serve as a basis for a standard measurement procedure of J_{Ic}. The technique which is considered most appropriate requires the use of at least four specimens to produce a crack growth resistance or R-curve. Although this multiple specimen procedure is somewhat more costly and time consuming than a single specimen procedure, it is considered to be the most accurate and also allows the evaluation of the ductile crack propagation properties of the material.

Specifically, the procedure requires that fatigue cracks be produced in each of the specimens to a crack length to specimen width ratio of $a/W > 0.5$. Each specimen is then loaded to different levels within the plastic region to produce different amounts of ductile crack growth, while the applied load and the load-line displacement is monitored. The specimens are then unloaded and the crack front is marked by either heat tinting, as in the case of the HY 130 steel specimens, or by fatigue post-cracking, as would be done for non-ferrous alloys. The amount of ductile crack growth (Δa) is then measured directly from the specimen surface and the corresponding J integral values are calculated (for three-point bend specimens with a specimen span-to-width ratio of $S/W = 4.0$) from the load-displacement diagram using the following equation:

$$J = 2A/Bb$$

where

A= the area under the load-displacement curve to the point of unloading (in-lb)

B= the specimen thickness (in)

b= the length of the uncracked ligament (in)

The calculated values of J are then plotted as a function of the ductile crack extension, Δa, and a straight line through these points is calculated to produce the so-called "R-line". A schematic R-curve is shown in Figure 1 which also illustrates the effect of crack tip blunting prior to

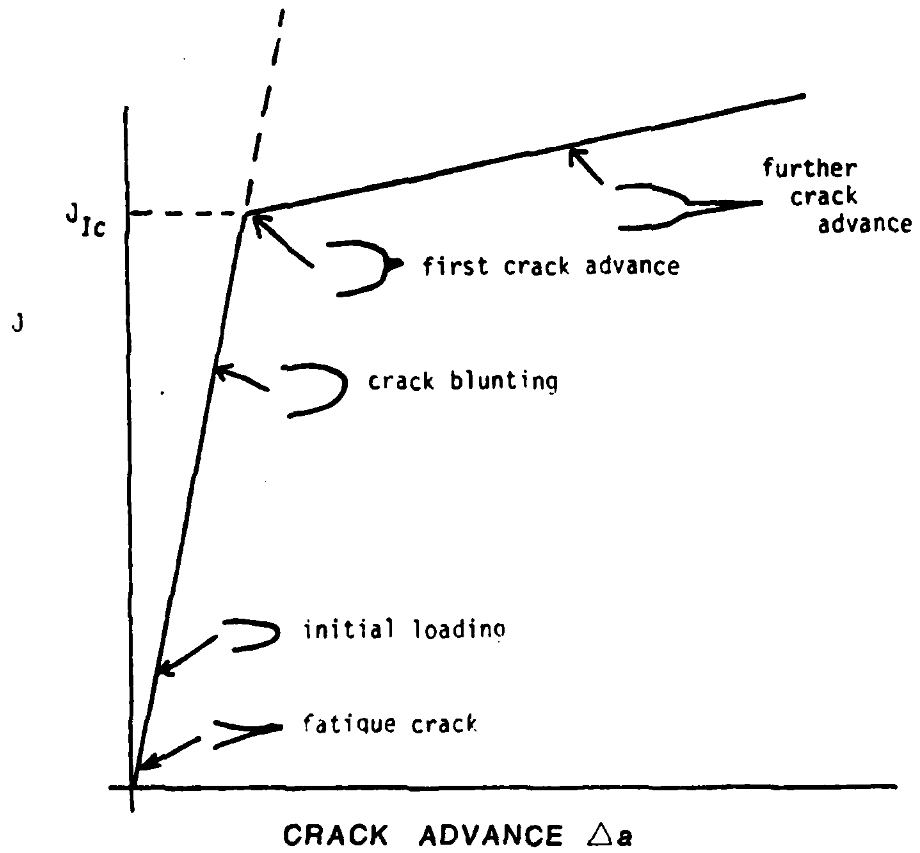

Figure 1. Schematic J - R Curve showing the changing crack tip condition.

crack initiation. The blunting line may be calculated from the equation:

$$J = 2\sigma_y \Delta a$$

where σ_y is the flow stress, usually expressed as the mean of the ultimate tensile and yield stresses (psi). The critical value of the J integral corresponding to ductile crack initiation, J_{Ic}, is then taken to be the intersection of the blunting and R-Lines. In addition to the critical initiation parameter, J_{Ic}, a measure of the resistance to crack propagation is also accomplished by calculation of the tearing modulus given by the equation:

$$T = \left(\frac{dJ}{da}\right) \frac{E}{\sigma_y^2}$$

where dJ/da is the slope of the R-line and E is Young's modulus. This parameter may be used in a relative sense to differentiate ductile and brittle materials. Ductile materials have a relatively large value of dJ/da, corresponding to a high resistance to crack extension. Conversely, brittle materials will possess a low tearing modulus.

The procedure for the determination of J_{Ic}, as suggested by ASTM Committee E24, was followed during this investigation, with the following exceptions:

a. Ductile crack extension was not limited to approximately 0.06 inches and possible non-linearities may have developed, but these are not immediately apparent.

b. The R-Line is not always defined by the required minimum of four data points within the valid crack extension region.

c. In order to reduce the total time required for testing, fatigue pre-cracks were produced using higher applied loads than those normally recommended.

d. Crack length and ductile crack extension were measured by simple three point averaging at the fracture surface, as opposed to the recommended nine point averaging procedure.

Load-line displacement is measured directly from linearly variable differential transformer (LVDT) of the lower ram of an MTS servo hydraulic testing system. A compliance correction is then applied to allow for elastic compression of the test fixture and indentation of the rollers into the specimen. An uncracked specimen is loaded to a load greater than that applied to the cracked specimens during testing and the area under the load versus load-line displacement is calculated for each specimen. This energy, corresponding to the test fixture compliance, is then subtracted from the measured areas under the original load-displacement curves. A typical load versus load-line displacement curve as originally measured by the LVDT and after compliance correction is shown in Figure 2.

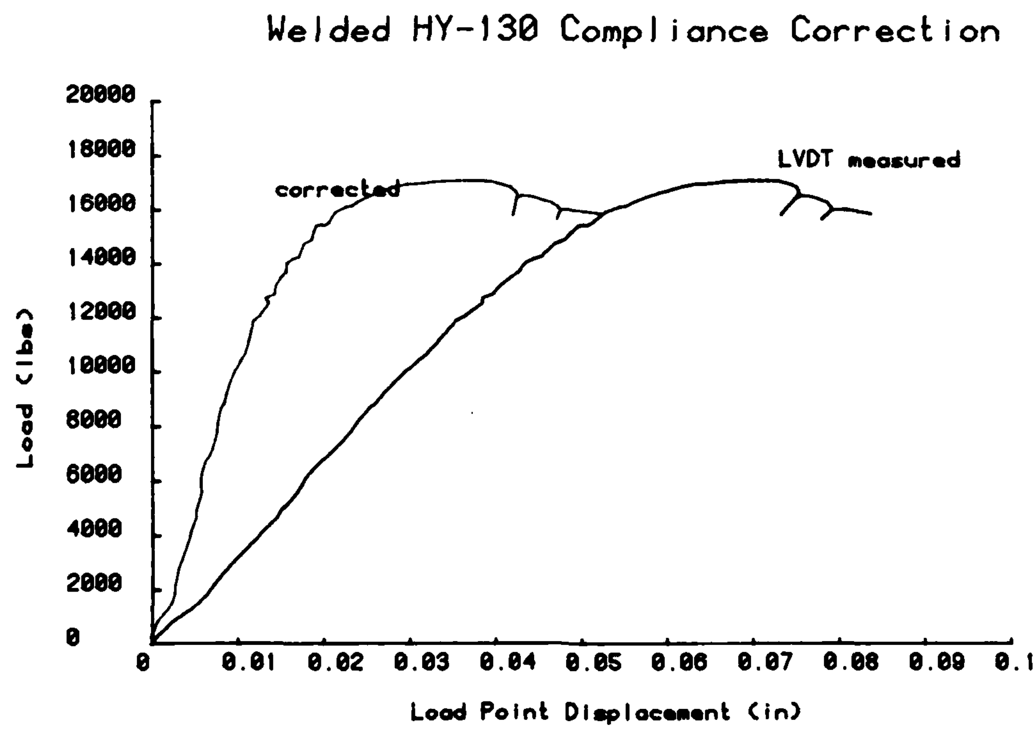

Figure 2. Typical load-displacement curve showing compliance correction.

HY 130 Steel Weldments

Previous investigations at DREP and the University of British Columbia have obtained data on the fatigue crack initiation properties[2], the Charpy V-notch impact properties[3] and the resistance to environmental cracking of HY 130 steel and its weldments[4]. The compositions of the HY 130 parent and weld metals are given in Table I.

TABLE I

		%C	%Ni	%Mn	%Cr	%Mo	%V	%Si	%S
HY 130	Parent	.1	5.3	.78	.59	.49	.06	.3	.012
E 14018	Weld	-	3.5	.9	.55	.64	-	-	.005

Additionally, both the static and dynamic J_{Ic} determinations have been made for the HY 130 parent material[5,8] and dynamic J_{Ic} measurements have been made for HY 130 weldments in the "as welded" and in the temper embrittled conditions by instrumented impact testing[5].

The pertinent conclusions reached during these investigations may be summarized as follows:

1. Significant temper embrittlement is induced in HY 130 weldments produced by an E14018 weld rod with subsequent stress relief heat treatment at 1150°F for two hours, followed by a furnace cooling procedure.

2. The fracture toughness estimated from slightly undersized specimens of E14018 welded HY 130 indicated values of K_c to be 113 KSI $\sqrt{in}$ and 112 KSI $\sqrt{in}$ in the "as welded" and temper embrittled conditions, respectively.

3. Charpy impact energies[3], however, decreased drastically upon temper embrittlement. Impact energies in excess of 50 ft-lb were measured for the "as welded" specimens at temperatures of -40°F, whereas the temper embrittled weld produced impact energies as low as 5 ft-lb at -40°F. Similar results were also obtained by Hawbolt[6] during his investigation of HY 130 temper embrittlement.

4. The value of J_{Ic} for parent AMVD HY 130 steel[8] was determined to be 670 in-lb/in^2, which corresponds to a K_{Ic} estimate of 148 KSI $\sqrt{in}$.

5. K_{Ic} estimates obtained from dynamic J_{Ic} measurements[5], produced during HAZ fracture, indicated values of 175 KSI $\sqrt{in}$ and 142 KSI $\sqrt{in}$ for the "as welded" and temper embrittled specimens, respectively.

The R-curve data for the "as welded" and temper embrittled weldments resulting from the present investigation are shown in Figure 3. The measured values of J_{Ic} are 733 in-lb/in^2 for the "as welded" material and 500 in-lb/in^2 for the temper embrittled material. The corresponding K_{Ic} estimates of 148 KSI $\sqrt{in}$ and 122 KSI $\sqrt{in}$ indicate the same trend as those measured by Hawbolt[6], however, these results also reflect an expected decrease in fracture toughness of the weld metal in comparison to HY 130 parent material. It has been demonstrated previously by Hawbolt[5] that crack initiation energies vary only slightly with temper embrittlement, whereas the crack propagation energies are very susceptible to this effect. Therefore, it is indeed reasonable that the fracture toughness initiation parameter, K_{Ic}, is relatively insensitive to changes in ductility. However, crack propagation parameters such as the tearing modulus should exhibit large relative changes with ductility. Examination of the two R-curves shows greatly different slopes (dJ/da) and, therefore, a decreased tearing modulus

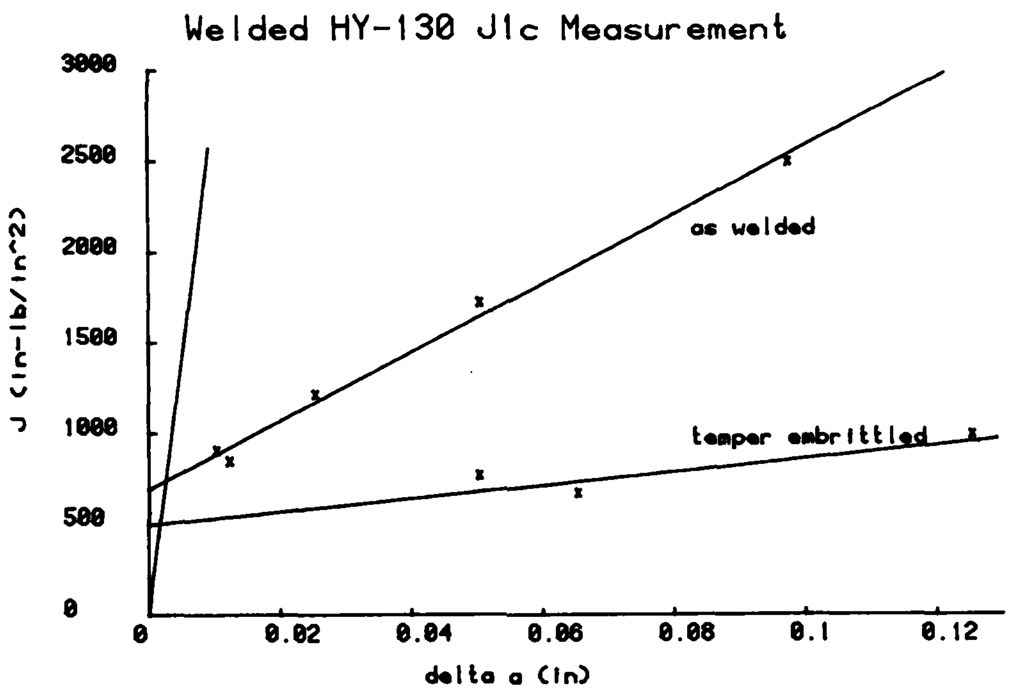

Figure 3. R - Curves for "as welded" and temper embrittled HY 130 weldments.

of the embrittled material. The calculated tearing modulus of the "as welded" material is found to be 30.2, whereas the tearing modulus falls to a value of 5.8 following temper embrittlement. This result agrees reasonably well with that of Gudas et al.[9] who measured a tearing modulus of T=34.4 in similar AMVD HY 130 steel.

After final fracture, the fracture surfaces of several specimens were examined in greater detail using the scanning electron microscope. Typical SEM micrographs of the crack front at the point of ductile crack extension for the "as welded" and temper embrittled specimens are presented in Figures 4 and 5, respectively. Examination of Figure 4b shows the presence of a small stretch zone followed by crack initiation and is indicative of high ductility. Examination of Figure 5b, the crack tip region of the embrittled

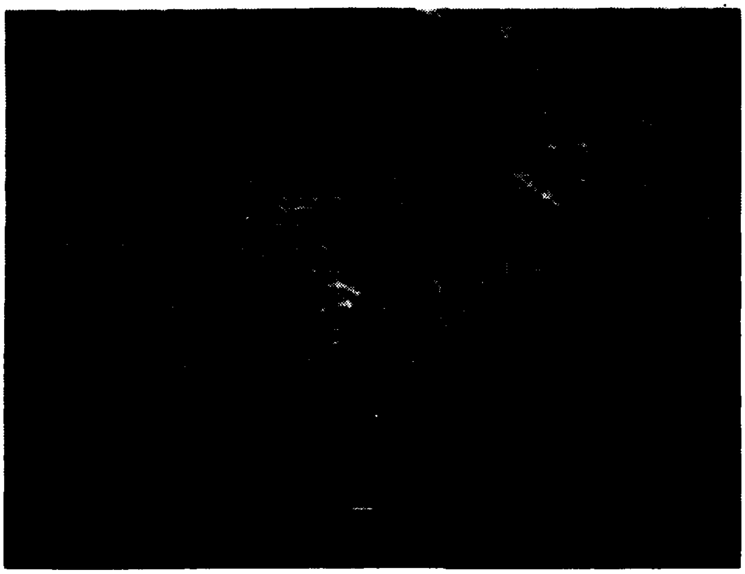

Figure 4a. SEM micrograph of "as welded" HY 130 crack tip x50

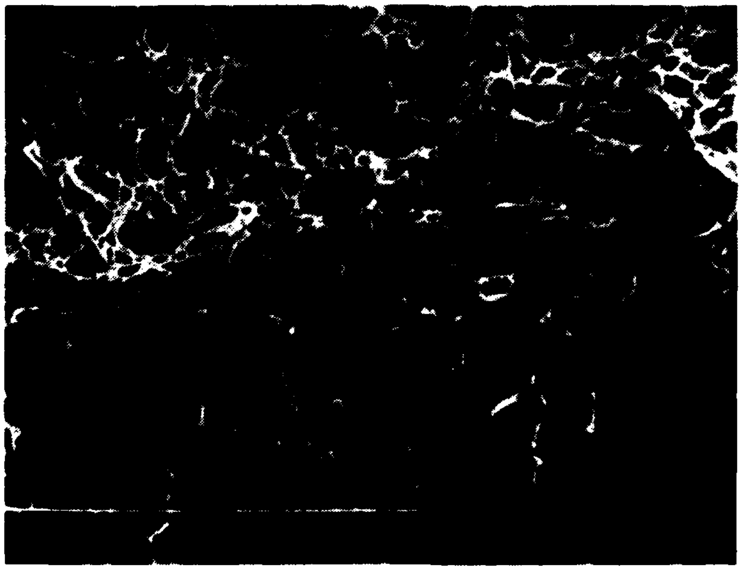

Figure 4b. SEM micrograph of "as welded" HY 130 crack tip x1050

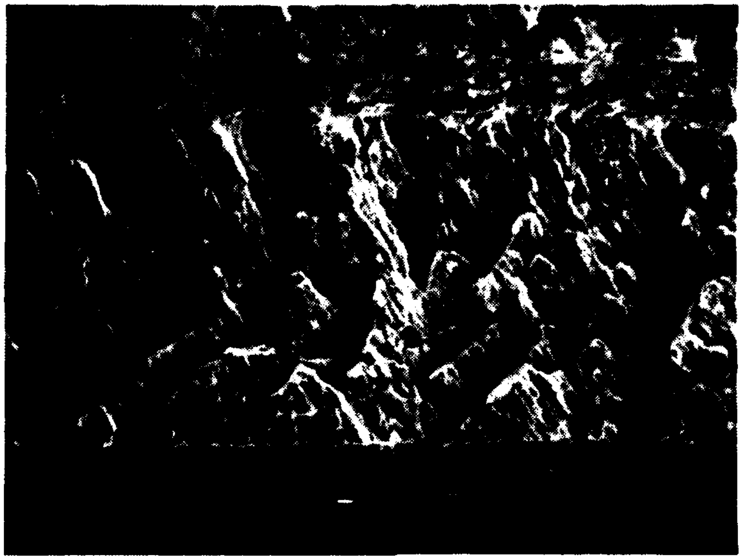

Figure 5a. Crack growth region of temper embrittled HY 130 weldment x35

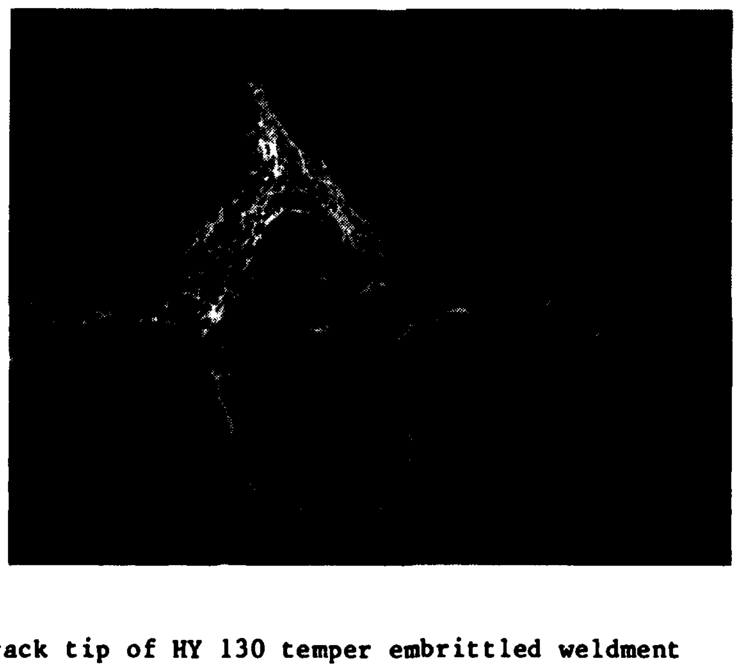

Figure 5b. Crack tip of HY 130 temper embrittled weldment x700

material, reveals a similar ductile behaviour at the point of crack initiation, however, the mode of crack propagation changes to an intergranular fracture mechanism which propagates along the grain boundaries of the large columnar grains of the embrittled weld. These results serve to confirm the differences noted previously regarding the initiation and propagation properties of these weldments. The condition of the crack tip is seen to be similar in both instances at the point of initiation. It is, therefore, reasonable that crack initiation in either material would require similar amounts of energy and produce similar values of J_{Ic}. The mode of crack propagation, however, differs considerably between the two material conditions. Intergranular crack propagation requires significantly less energy than propagation by microvoid coalescence. The difference noted in the tearing moduli of the weldments in the "as welded" and temper embrittled conditions is, therefore, a direct result of the mechanism of crack propagation.

Conclusions

1. Apparent anomalies in the fracture behaviour of temper embrittled weldments of HY 130 may be explained in terms of their crack initiation and propagation properties. Crack initiation properties, such as plane strain fracture toughness (K_{Ic}) or ductile fracture toughness (J_{Ic}), are relatively insensitive to changes in material ductility. However, crack propagation energies are very susceptible to changes in ductility. Relative ductility measurements would be best accomplished utilizing parameters such as the measured crack propagation energy during instrumented impact Charpy V-notch testing or the ductile tearing modulus.

2. The measured fracture toughness values for the "as welded" and the temper embrittled E14018, HY 130 weldments are 733 in-lb/in^2 and 500 in-lb/in^2, respectively. These values correspond to plane strain fracture toughness estimates of 148 KSI$\sqrt{\text{in}}$ and 122 KSI$\sqrt{\text{in}}$, respectively.

3. The ductile tearing moduli for these same weldments are 30.2 and 5.5, respectively. The "as welded" value indicates only a slight weld embrittlement in comparison to the literature value of 34.4. The temper embrittled material has lost a great amount of ductility, as evidenced by the low tearing modulus.

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3. DOCUMENT TITLE
Crack Initiation and Propagation Properties of HY 130 Steel Weldments Following Temper Embrittlement

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
DREP Materials Report

5. AUTHOR(S) (Last name, first name, middle initial)

McRae, K. I.

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